Modal Variability of the Southern Ocean

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Wind stress is one of the main forces driving the ocean circulation. The ocean responds to synoptic variability of the atmosphere by generating so-called barotropic flows—these motions reach all the way to the ocean floor, and are not influenced by the density stratification of the ocean. The resulting currents are hence strongly steered by the topography of the ocean floor. In fact, currents do not like to flow across isobaths, since the resulting stretching or squeezing of the water column requires a change in a quantity called vorticity (the continuum-mechanical equivalent of angular momentum). This gives special significance to a few basins where isobaths (or more precisely, contours of potential vorticity H/f, where f is twice the local rotation rate of the Earth and H is ocean depth) are closed onto themselves. These areas can often be identified using altimeters (satellite-borne instruments that measure sea-surface height from space), since the circulation is particularly energetic. Examples are the Argentine Basin, the Mascarene Basin, and the Australia-Antarctic Basin, an abyssal plain in the Indian sector of the Southern Ocean.

An appropriate way to describe the circulation in these basins is in terms of modes. Modes are specific circulation patterns that retain their spatial coherence when evolving in time. A category of modal circulation patterns is flows along contours of H/f. These motions are, in a sense, balanced: once such a flow is generated (excited) by wind stress, it decays only slowly under the influence of frictional processes. Information about modal decay can help us to constrain the energy pathways in the ocean—work done by the winds is the most important energy source for the ocean, and an important part will be used to mix water masses and drive the global overturning circulation (see Fig. 1).
A few studies have hypothesized that enhanced variability in the Australia-Antarctic Basin can be explained by the excitation of modes. However, their estimates of the decay time scale suggested that these modes decay in only a few days, apparently at odds with a slow, frictional spin-down mechanism. In a recent paper [1] we addressed this discrepancy, using a combination of theory, numerical modeling, and observations. First, we calculated the normal modes in a numerical model of the Southern Ocean to show that the observed enhanced variability is indeed consistent with the excitation of barotropic modes (Fig. 1). Then, by projecting these modes on altimeter data, we confirmed their apparent rapid decay. Subsequent numerical analysis revealed the reason for this: arbitrary circulation patterns, like those generated continuously by the synoptic atmospheric variability, have only a small projection onto the actual mode—the remainder can be considered unbalanced flow. The apparent rapid decay reflects the disintegration of the unbalanced flow only—it can take a week for the unbalanced flow to die out and reveal the decay of the balanced, modal circulation. Since altimeter data seems to be unsuitable for estimating the mixing efficiency, we have to rely on field programs (involving current meter moorings) to provide us with the appropriate data.

Another category of modes is characterized by oscillatory motions, and is equivalent to so-called planetary basin modes. These modes can be described as a superposition of planetary waves and their reflections in a closed basin. However,

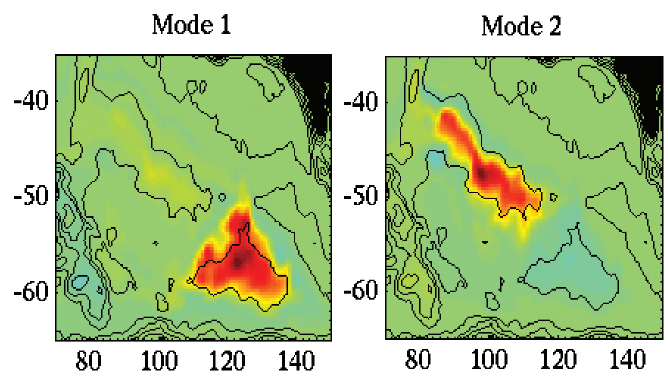

Fig. 1. The two dominant topographically trapped modes of the Australia-Antarctic Basin. Shown are their expressions in sea-surface height. The associated circulation is in the anticlockwise sense around these high-pressure areas. Their natural decay time scale is of the order of 3 weeks.

unequivocal observations of such modes were absent until a very energetic, bimonthly oscillation was found in the Mascarene Basin. Weijer [2] showed that this oscillation is indeed consistent with the excitation of a planetary basin mode. However, the application of classical theory is indeed challenging when the bathymetry is more complicated. Case in point is the Argentine Basin, an abyssal plain with a pronounced seamount (Zapiola Rise) in its center. Previous observations indicated the presence of very energetic oscillations, but estimates of the dominant periodicity ranged from 19 to 28 days. Weijer et al. [3] predicted that the Argentine Basin could house no fewer than four distinct modes, with periods between 19 and 32 days. The spatial patterns of these modes are rather spectacular, as they consist of dipoles in sea-surface height that rotate (in 3 to 4 weeks time) around Zapiola Rise (Fig. 2). By projecting the modes (obtained as eigenmodes from the model) onto altimeter data, we were able to show that each of these modes becomes excited in the Argentine Basin. It took a complicated exercise to show that these rotating modes are indeed equivalent to the planetary basin modes of classical theory[4].

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[1] W. Weijer, S.T. Gille, F. Vivier, "Modal decay in the Australia-Antarctic Basin." Submitted to *J. Phys. Ocean.* (2009).
[2] W. Weijer, *Deep-Sea Res. I* **55,** 128-136 (2008).
[3] W. Weijer et al., *J. Phys. Ocean* **37,** 2855-2868 (2007).
[4] W. Weijer et al., *J. Phys. Ocean* **37,** 2869-2881 (2007).

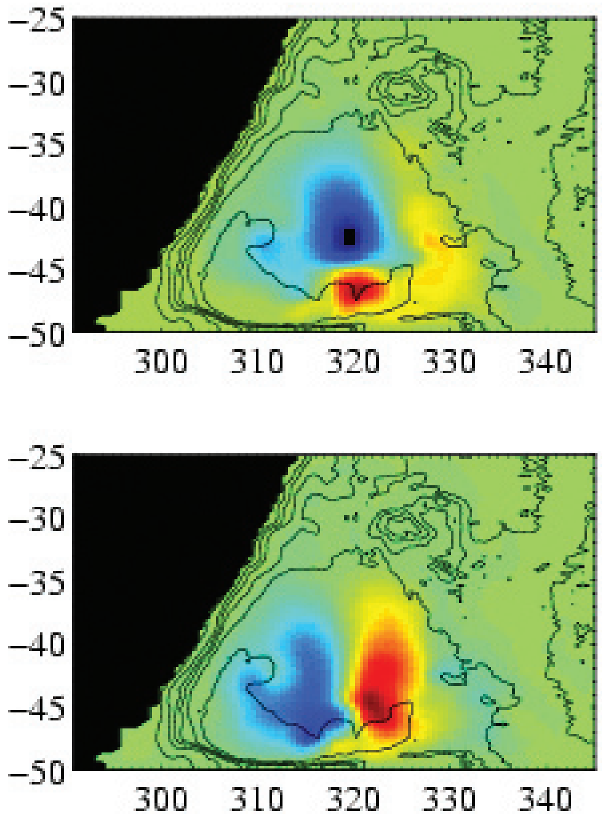

Fig. 2. The dominant oscillatory mode of the Argentine Basin, as expressed in sea-surface height (SSH). The plots show two subsequent phases of an oscillatory cycle, and clearly suggest rotation of the lobes of high (red) and low (blue) sea level around Zapiola Rise. The Argentine Basin is bounded in the west by the South American continent, in the south by the Falkland Escarpment, in the east by the mid-Atlantic ridge, and in the north by the Rio Grande Rise. Depth is indicated by contours at 1000-m increments. The cycle completes in about a month.

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